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## Second Law Analysis of Bubbling Fluidized Bed Gasifier for Biomass Gasification

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### 1. Introduction

The management of refused derived fuel (RDF) is one of the most significant problems especially for developing countries. Technologies to convert biomass energy already exist as well. Gasification through a bubbling fluidized bed gasifier (BFBG) is discussed in this context. A BFBG is able to deal with wide variety of fuels due to the presence of inert bed material, in which bubbles mix turbulently under buoyancy force from a fluidizing agent like air or oxygen [1]. Under such violent bed conditions biomass waste particles are able to react fully to release volatiles as a result from high solids contact rate. Gases are released from the biomass particles and can then be used for producing electricity. In the literature there are several investigations on gasification processes from the thermodynamic point of view. Altafini and Mirandola [2] presented a coal gasification model by means of chemical equilibrium, minimizing the Gibbs free energy. The authors studied the effect of the ultimate analysis and the gasifying agents/fuel ratio on the equilibrium temperature (adiabatic case) in order to obtain the producer gas composition and the conversion efficiency. They concluded that the equilibrium model fits the real process well. Similar conclusions for biomass gasification are presented by the same authors [3], simulating the gasifying process in a downdraft gasifier, where the object of study was the effect of the biomass moisture content on the final gas composition assuming chemical equilibrium. Lapuerta et al. [4] predicted the product gas composition as a function of the fuel/ air ratio by means of an equilibrium model. A kinetic model was used to establish the freezing temperature, which is used for equilibrium calculations in combination with the adiabatic flame temperature. The biomass gasification process was modeled by Zainal et al. [5] based on thermodynamic equilibrium. They analysed the influence of the moisture content and reaction temperature on the product gas composition and its calorific value. Ruggiero and Manfrida [6] emphasized the potential of the equilibrium model considering the Gibbs free energy. This proceeding can be used under different operating conditions for predicting producer gas composition and the corresponding heating value.

Many studies on the modeling of coal gasifiers, in general, and coal gasification in bubbling fluidized beds, in particular, can be found in the literature. Nevertheless, thermodynamic modeling of the biomass gasification in bubbling fluidized beds has not been amply addressed. A few articles on the modeling of biomass bubbling fluidized bed gasifiers

(BBFBGs) can be found in the literature. In modeling the biomass gasification (with air) in bubbling fluidized beds (BFBG), Belleville and Capart [7] developed an empirical model which was successfully applied to the biomass gasifier of Creusot Loire in Clamecy (France). Fan and Walawender [8] and Van den Aarsen [9] reported two of the pioneering models, which are well known today; Corella et al. [10] modeled some non-stationary states of BFBGs; Bilodeau et al. [11] considered axial variations of temperature and concentration and applied their results to a 50 kg/h pilot gasifier; Jiang and Morey [12,13] introduced new concepts in this modeling, especially related to the freeboard and the fuel feed rate; Hamel and Krumm [14] provided interesting axial profiles of temperature, although their work was mainly focused on gasification of coal and did not give many details of their model; Mansaray et al. [15,16] presented two models using the ASPEN PLUS process simulator.

In this work the equilibrium modeling of BFBG has been applied for the biomass waste gasification. The model employs equilibrium constants of all constituent reactions, in addition, the effect of the fuel/air ratio, moisture content of the fuel and gasifying temperature on the mole fraction of product gases of RDF gasification and corresponding higher heating value of it. Moreover, the exergetic efficiency and cold gas efficiency of the BFBG has been evaluated.

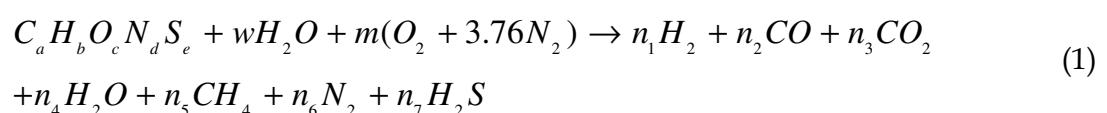
## 2. The model of the BFBG

### 2.1 Energy analysis

The idealized fluidized bed gasifier model is used with the following assumptions:

(i) The chemical equilibrium between gasifier products is reached, (ii) the ashes are not considered and (iii) heat losses in the gasifier are neglected.

The global gasification reaction can be written as follows:



In which the  $C_a H_b O_c N_d S_e$  is the substitution fuel formula which can be calculated by the ultimate analysis of the fuel and the mass fractions of the carbon, hydrogen, oxygen, nitrogen and sulphur. "m" and "w" are the molar quantity of air entering the gasifier and moisture molar fraction in the fuel, respectively. The variable "m" corresponds to the molar quantity of air used during the gasifying process which is entering the BFBG at the temperature of 120°C and the pressure of 45 bar and depends on the gasification relative fuel/air ratio and the stoichiometric fuel/air ratio relating to the biomass waste as a fuel[17]

$$m = \frac{1}{F_{rg}} F_{st} \quad (2)$$

And w is determined from the moisture content of the fuel

$$w = \frac{M_{BM} \phi}{M_{H_2O} (1 - \phi)} \quad (3)$$

On the right-hand side,  $n_i$  are the numbers of mole of the species i that are unknown.

In a fluidized bed gasifier, nearly the entire sulfur in the feed is converted to  $H_2S$ , which must be effectively removed to ensure that the sulfur content of the final gas is within

acceptable limits. In the case of fluidized bed gasifiers, limestone can be fed into the gasifier along with coal to capture most of the H<sub>2</sub>S produced within the bed itself. The limestone (CaCO<sub>3</sub>) calcines inside the gasifier to produce lime (CaO), which in turn is converted to calcium sulfide (CaS) upon reaction with the H<sub>2</sub>S inside the gasifier.



The substitution fuel formula  $C_aH_bO_cS_dN_e$  can be calculated Starting from the ultimate analysis of the biomass waste and the mass fractions of the carbon, hydrogen, oxygen, nitrogen and sulphur (C, H, O, N, S), assuming a= 1, with the following expressions:

$$b = \frac{HM_c}{CM_H}, c = \frac{OM_c}{CM_O}, d = \frac{NM_c}{CM_N}, e = \frac{SM_c}{CM_S} \tag{6}$$

Ultimate analysis of the biomass waste (RDF) used in this model is shown in Table 1.

Waste Fuel	C%	H%	O%	N%	S%	Ash	HHV(MJ/Kg)
RDF	44.7	6.21	38.6	0.69	0.00	10.4	19.495

Table 1. Ultimate analysis of RDF (dry basis, weight Percentage) [18]

From the substitution fuel formula, the specific molecular weight of the biomass waste, the molar quantity of water per mole of biomass waste, the stoichiometric fuel/air ratio and the formation enthalpy of the biomass waste can be calculated. Now for calculating the molar quantity of the product gases 7 equations are needed: From the molar biomass waste composition  $C_aH_bO_cS_dN_e$  and the molar moisture quantity, the atomic balances for C, H, O, N and S are obtained, respectively

$$\begin{aligned} C : a &= n_2 + n_3 + n_5 \\ H : b + 2w &= 2n_1 + 2n_4 + 4n_5 \\ O : c + w + 2m &= 2n_2 + n_3 + n_4 \\ N : d + 2m \times 3.76 &= 2n_6 \\ S : e &= n_7 \end{aligned} \tag{7}$$

There are now only 5 equations to calculate 7variables. To solve the system, two other equations should be added. From the first assumption, two equations in equilibrium can be used. Chemical equilibrium is usually explained either by minimization of Gibbs free energy

or by using an equilibrium constant. To minimize the Gibbs free energy, constrained optimization methods are often used which requires a realizing of complex mathematical theories. For that reason, the present thermodynamic model is developed based on the equilibrium constant. Therefore, the remaining two equations were obtained from the equilibrium constant of the reactions occurring in the gasification zone as shown below:

In the reduction zone of the gasifier, hydrogen is reduced to methane by carbon (methanation reaction).



Methane formation is preferred especially when the gasification products are to be used as a feedstock for other chemical process. It is also preferred in IGCC applications due to methane's high heating value.

The equilibrium constant  $K_1$  relates the partial pressures of the reaction as follows:

$$K_1 = \frac{(P_{CH_4} / P_{total})}{(P_{H_2} / P_{total})^2} \quad (9)$$

Or as a function of the molar composition, assuming the behavior of the product gas to be ideal,

$$K_1 = \frac{n_5 \times n_{total}}{n_1^2} \quad (10)$$

The second reaction, also known as the water gas shift reaction, describes the equilibrium between CO and H<sub>2</sub> in the presence of water



The heating value of hydrogen is higher than that of carbon monoxide. Therefore, the reduction of steam by carbon monoxide to produce hydrogen is a highly desirable reaction. The corresponding equilibrium  $K_2$  constant is obtained as follows:

$$K_2 = \frac{(P_{CO_2} / P_{total})(P_{H_2} / P_{total})}{(P_{CO} / P_{total})(P_{H_2O} / P_{total})} \quad (12)$$

Or as a function of the molar composition of the gas

$$K_2 = \frac{n_1 n_3}{n_2 n_4} \quad (13)$$

The values of the equilibrium constants  $K_1$  and  $K_2$  are calculated from the Gibbs free energy

$$K_p = \exp(-\Delta G_T^0 / R_u T) \quad (14)$$

Where  $\Delta G_T^0$  is the difference of the Gibbs free energy between the products and the reactants:

$$\Delta G^0_T = \Delta H^0 - T \Delta S^0$$

(15)

Substituting the Gibbs free energy in Eqs. (5) and (8), the equilibrium constants are obtained as

$$K_1 = \exp \left( - \left( G^0_{T,CH_4} - 2G^0_{T,H_2} \right) / R_u T \right)$$

(16)

$$K_2 = \exp \left( - \left( G^0_{T,H_2} + G^0_{T,CO_2} - G^0_{T,CO} - G^0_{T,H_2O} \right) / R_u T \right)$$

(17)

With

$$G^0_{T,i} = \Delta \tilde{h}^0_{f,298} + \int_{298}^T \overline{C}_p(T) dT - Ts^0$$

(18)

Where  $\overline{C}_p(T)$  is the specific heat at constant pressure in (J/mol K) and is a function of temperature. It can be defined by empirical equation below.

$$\overline{C}_p(T) = A + BT + CT^2 + DT^3$$

In which the coefficients are obtained from the table 2

$\overline{C}_p(T) = A + BT + CT^2 + DT^3$ (J/mol K)				
compound	A	$B \times 10^2$	$C \times 10^5$	$D \times 10^8$
$H_2$	29.062	-0.82	0.199	0.0
$O_2$	25.594	13.251	-0.421	0.0
CO	26.537	7.683	-0.1172	0.0
CO <sub>2</sub>	26.748	42.258	-1.425	0.0
CH <sub>4</sub>	25.36	1.687	7.131	-4.084

Table 2. Heat capacity of an ideal gas[19]

Gasifying temperature

For calculating K1 and K2, the temperature in the gasification or reduction zone must be known. It should be noted that in bubbling fluidized bed the bed, temperature will be in the range of 900-1200°K by which the equilibrium constants will be calculated.

Enthalpy definition

After defining the corresponding equations, Because of nonlinear nature of some of the equations the Newton-Raphson method has been used to calculate the values n1-n7. The enthalpy of the product gas is

$$\overline{h} = \sum_{i=prod} x_i \left( \overline{h}_{f,i}^0 + \Delta \overline{h}_{T,i} \right) \tag{19}$$

where  $x_i$  is mole fraction of species  $i$  in the ideal gas mixture and  $\overline{h}_f^0$  is the enthalpy of formation and  $\Delta \overline{h}_T$  represents the enthalpy difference between any given state and at reference state. It can be approximated by

$$\Delta \overline{h}_T = \int_{298}^T \overline{C}_p(t) dT \tag{20}$$

Table 3 shows some the value of  $\overline{h}_f^0$  for some gas components.

Compound	$\overline{h}_f^0$ (kJ/mol)
$H_2$	0.0
$O_2$	0.0
$CO$	-110.52
$CO_2$	-393.51
$CH_4$	-74.85
$H_2O(l)$	-285.84
$H_2S$	-20.501[21]
$SO_2$	-296.833[21]

Table 3. Enthalpy of formation at the reference state [20]

It should be noted that enthalpy of formation for solid fuel can be calculated as:

$$h_{f,bm} = HHV_{db} + \frac{1}{M_{bm}} \sum_{i=prod} \tilde{\nu}_i h_{f,i} \tag{21}$$

Where  $(\overline{h}_f^0)_k$  is the enthalpy of formation of the product  $k$  under the complete combustion of the solid and  $HHV$  is the higher heating value of the solid fuel.

Heat of formation of any biomass waste material can be calculated with good accuracy from the following equation[22]:

$$\Delta H_c = \overline{HHV} (KJ / Kmol) = 0.2326(146.58C + 56.878H - 51.53O - 6.58A + 29.45) \tag{22}$$

Where C, H, O and A are the mass fractions of carbon, hydrogen, oxygen and Ash, respectively in the dry biomass waste.

2.2 Exergy analysis

The entropy of ideal gas is represented by:

$$S = \overline{S}^0 + \int_{T_o}^T \frac{\overline{C}_p}{T} dT - R \ln \frac{P}{P_o} \tag{23}$$

Where P is the pressure of the bubbling fluidized bed gasifier, and  $\overline{S}^0$  is entropy at reference state. Table 4 shows some components  $\overline{S}^0$

Compound	$\overline{S}^0$ (J/molK)
$H_2$	130.59
$O_2$	205.03
$CO$	197.91
$CO_2$	213.64
$CH_4$	186.19
$H_2O(l)$	69.94
$H_2S$	205.757[21]
$SO_2$	284.094[21]

Table 4. Entropy at the reference state(at  $T_{ref}$ =298.15K(25°C), $p_{ref}$ =1 bar) [20]

The exergy of the product gas is comprised of two components: Exergy chemical exergy ( $E^{CH}$ ) and physical exergy ( $E^{PH}$ ). Total exergy of the product gas is given as

$$E_{pg} = E^{PH} + E^{CH} \tag{24}$$

The physical exergy is the maximum theoretical work obtainable as the system( here the product gas) passes from its initial state where the temperature is the gasifying temperature and the pressure equals the gasifier pressure to the restricted dead state where the temperature is  $T_0$  and the pressure is  $P_0$  and is given by the expression

$$E^{PH} = (H - H_o) - T_o (S - S_o) \tag{25}$$

The physical exergy of gas mixture per mole is derived from the conventional linear mixing rule

$$\overline{e}^{PH} = \sum x_i \overline{e}_i^{PH} \tag{26}$$



The chemical exergy is the maximum theoretical useful work obtainable as the system passes from the restricted dead state to the dead state where it is in complete equilibrium with the environment.

And chemical exergy of gas mixture is given by

$$\overline{e}^{CH} = \sum_i x_i \overline{\epsilon}_{0,i}^{CH} + RT_0 \sum_i x_i \ln x_i \tag{27}$$

Where  $\overline{\epsilon}_{0,i}^{CH}$  is the standard chemical exergy of a pure chemical compound i which is available in Table 5 for some gas components.

Substance	$\overline{\epsilon}_{0,i}^{CH}$ (kJ / kmol)
$H_2$	238490
$CO$	275430
$CO_2$	20140
$H_2O(g)$	11710
$CH_4$	836510
$N_2$	720
$H_2S$	812000[21]
$SO_2$	313.4[21]

Table 5. Standard chemical exergy of some substances at 298.15K and p<sub>0</sub>[21]

Special considerations apply for the gasifying products when evaluating the chemical and physical exergy. When a product gas mixture is brought to P<sub>0</sub>, T<sub>0</sub>, some consideration would occur: At 25°C, 1 atm, the mixture consists of H<sub>2</sub>, CO, CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>, together with saturated water vapor in equilibrium with saturated liquid. So it would be required to calculate the new composition at the dead state including the saturated liquid. Then the  $\overline{h}_o$  and  $\overline{s}_o$  values required to evaluate the physical exergy and the product gas mole fraction at the dead state essential for evaluating the chemical exergy can be calculated.

The exergy components and the total exergy for the moisture content of the fuel is obtained

$$E_{mois}^{PH} = w \left[ \overline{h} - \overline{h}_{f,liq}^0 - T_0 (\overline{s} - \overline{s}_{H_2O(l)}^0) \right] \tag{28}$$

$$E_{mois}^{CH} = w \times \overline{\epsilon}_{0,H_2O(l)}^{CH} \tag{29}$$

$$E_{mois} = E_{mois}^{CH} + E_{mois}^{PH} \tag{30}$$

Exergy for the fluidizing air entering the fluidized bed is defined with molar analysis of 0.21% O<sub>2</sub> and 0.79% N<sub>2</sub> with the pressure of 45 bar and the temperature of 373 °K , by using equations 25 and 26

$$E_{air} = E_{air}^{CH} + E_{air}^{PH}$$

(31)

For a biomass waste the chemical exergy is obtained as follows

$$\epsilon_{0,biomass} = \beta HHV_{biomass}$$

(32)

The factor  $\beta$  is the ratio of the chemical exergy to the HHV of the organic fraction of biomass waste. This factor is calculated with the following correlation [18]:

$$\beta = \frac{1.0412 + 0.216(Z_o / Z_c) - 0.2499Z_o / Z_c [1 + 0.7884Z_o / Z_c] + 0.045Z_N / Z_c}{1 - 0.3035Z_o / Z_c}$$

(33)

$Z_o$ ,  $Z_c$ ,  $Z_H$  and  $Z_N$  are the weight fractions of oxygen, Carbon, Hydrogen and Nitrogen, respectively in the biomass waste.

Therefore the total exergy of the biomass waste as a fuel can be defined:

$$E_{fuel} = \bar{\epsilon}_{0,biomass} \times n_{fuel}$$

(34)

2.3 Heating value and efficiencies

2.3.1 Heating value

The heating value of the producer gas can be obtained as the sum of the products of the molar fractions of each of the energetic gases (CO, H<sub>2</sub> and CH<sub>4</sub>) with its corresponding heating value (Table 6).

gas	HHV (MJ/kg mol)	LHV (MJ/kg mol)
CO	282.99	282.99
H <sub>2</sub>	285.84	241.83
CH <sub>4</sub>	890.36	802.34
H <sub>2</sub> S	562.59	518.59

Table 6. Heating value of combustible gases

2.3.1 Evaluation of the efficiency

It is assumed that the fluidized bed gasifier operates as adiabatic and pseudo-homogeneous reactor at atmospheric pressure.

Gasification entails partial oxidation of the feedstock, so chemical energy of biomass waste is converted into chemical and thermal energy of product gas.

The first law thermodynamic or cold gas efficiency can be defined as the relation between the energy leaving the gasifier i.e. the energy content of the producer gas, and the energy

entering the gasifier, i.e. the biomass waste and moisture. We assume the gas leaves the process at the reference temperature (25 °C), loosing the energy corresponding to its sensible enthalpy, and define the cold gas efficiency  $\eta_{Cg}$  as

$$\eta_{Cg} = \frac{HHV_{gas}}{HHV_{biomass}} \tag{35}$$

Where  $HHV_{gas}$  and  $HHV_{biomass}$  are the net heats of combustion (lower heating values) of gas and biomass waste, respectively.  
The exergetic efficiency may be defined as the ratio between chemical exergy as well as physical exergy of product gas and the total exergy of the entering streams i.e. the biomass waste and the moisture and fluidizing air.

$$\eta_{Ex} = \frac{\dot{E}_{out}}{\dot{E}_{in}} = \frac{\dot{E}_{pg}}{\dot{E}_{air} + \dot{E}_{mois} + \dot{E}_{fuel}} \tag{36}$$

In this work variations of the exergy efficiency, cold gas efficiency and product gas concentration will be investigated as a function of temperature, gasifying fuel/air ratio ( $F_{rg}$ ), and moisture content of the fuel ( $\varphi$ ).

3. Results and discussion

3.1 Validation of the model

The model presented in this article has been compared to the experimental work for the wood particles presented by Narvaez et al. [23]. By way of illustration the predicted HHV producer gas by the model and the results from the experiments are presented in Figure 1.

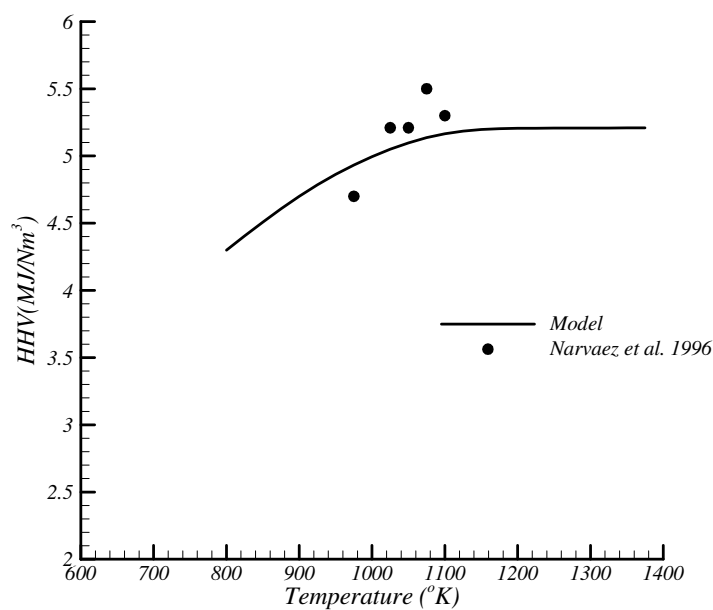


Fig. 1. Higher heating values of product gas at different temperatures for wood particles

### 3.2 Sensitivity analyses

The effect of  $F_{rg}$  on product gas composition and higher heating value for RDF gasification is presented in Figure 2. An increase in  $F_{rg}$  brings about an increase in the concentration of  $H_2$  and  $CO$  and a substantial decrease in  $CO_2$  concentration in dry gas product. This is because of the decreasing role of the char combustion in the bed compared to its gasification reaction, which results in higher concentration of combustible gases and lower  $CO_2$ .

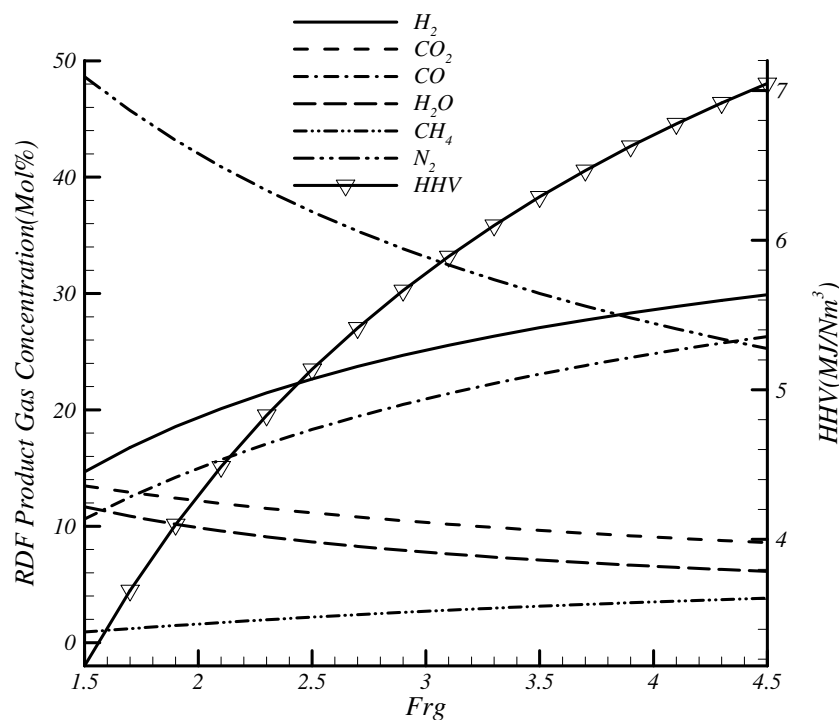


Fig. 2. Concentration of product gases and higher heating value at different  $F_{rg}$  values and  $T_{bed} = 1100^\circ K$ .

The effect of moisture content of the fuel on product gas composition and higher heating value for RDF gasification is presented in Figure 3. As shown in the figure, an increase in moisture content brings about an increase in the concentration of  $H_2$  and  $CH_4$  and decrease in the concentration of  $CO$ . This is because of the increasing role of the moisture content of the fuel and effect of the methanation reaction (equation 8) and the water-gas shift reaction (equation 11) in which the molar concentration of the  $CO$  decreases because of the reaction with  $H_2O$  and production of  $H_2$ , and resulting an increase in the molar quantity of  $CH_4$ . Therefore the higher heating value will decrease as the moisture content increases.

The effect of gasifying temperature on product gas composition is shown in Figure 4. The figure shows that an increase in temperature brings about an increase in the concentration of  $H_2$  and  $CO$  of RDF. This is because of the increasing role of the temperature in the equilibrium constants (16), (17) in which the equilibrium constant is dependent on the BFBG temperature, so an increase in temperature causes more production of combustible gases. The higher heating value in this temperature range at the constant  $F_{rg}$  is to some extent constant that is valid according to experimental works [22].

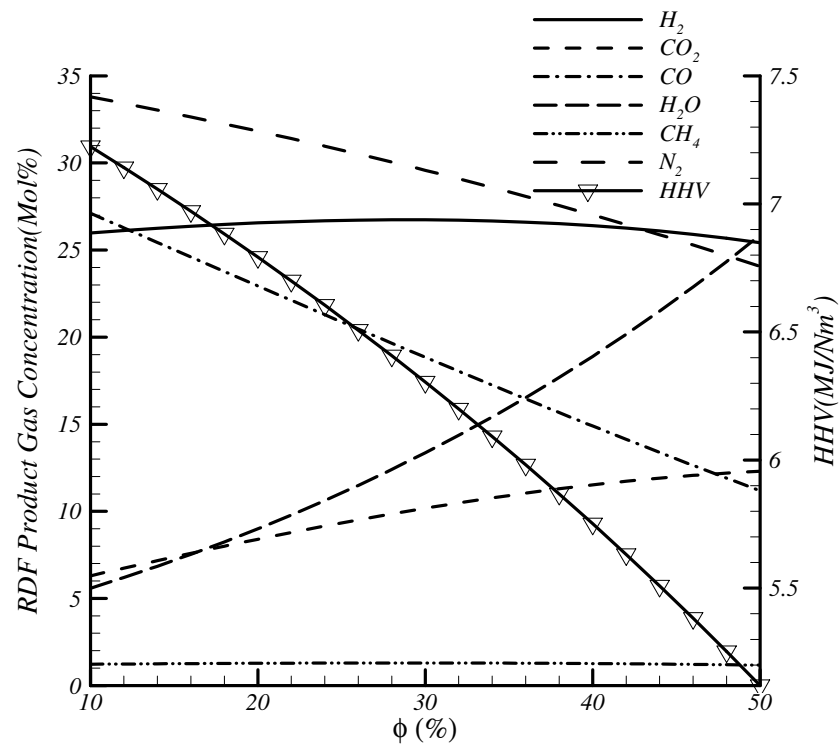


Fig. 3. Concentration of product gases and higher heating value at different moisture content of the fuel at  $T_{bed} = 1100^{\circ}K$  and  $F_{rg}=3$ .

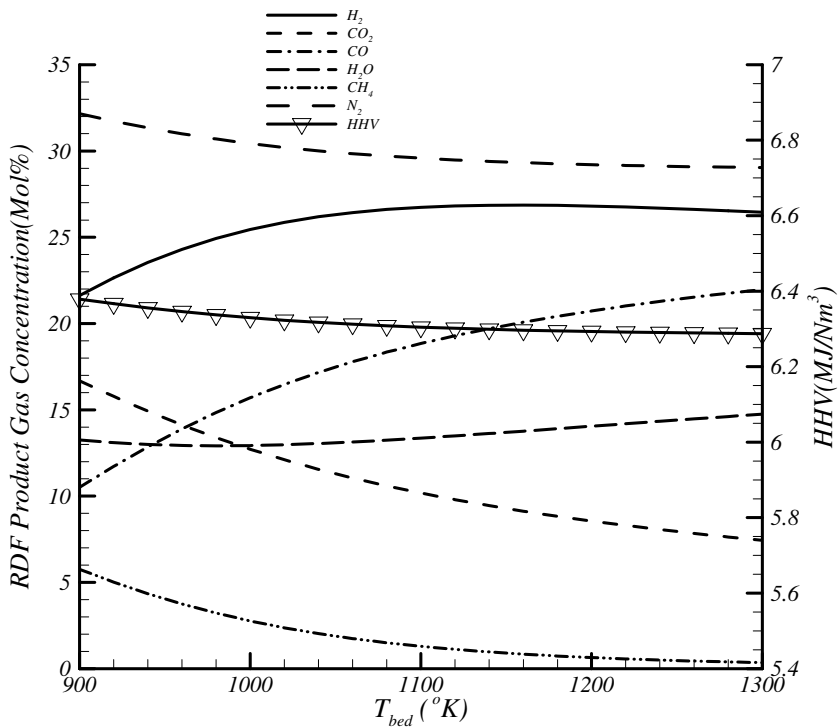


Fig. 4. Concentration of product gases and higher heating value at various gasifying temperatures at  $F_{rg}=3$

The effect of  $F_{rg}$  with moisture content of the fuel on exergetic efficiency and cold gas efficiency for RDF gasification are presented (by line & flood contour type) in Figures 5, 6. It is shown that the exergetic efficiency of BFBG increases with rising fuel/air ratio because when less air is admitted to the process, the variations in mole fractions of product gases will influence the exergy of the product in comparison to exergy of the fuel. Higher moisture content will increase the exergetic efficiency because of its considerable effect on enthalpy of the product gases (figure5). An increase in  $F_{rg}$ , as discussed before, brings about an increase in the concentration of combustible gases and higher heating value which yields an increase in cold gas efficiency and an increase in moisture content of the fuel, as discussed before, causes decrease in the concentration of combustible gases and higher heating value which yields a decrease in the cold gas efficiency (figure6).

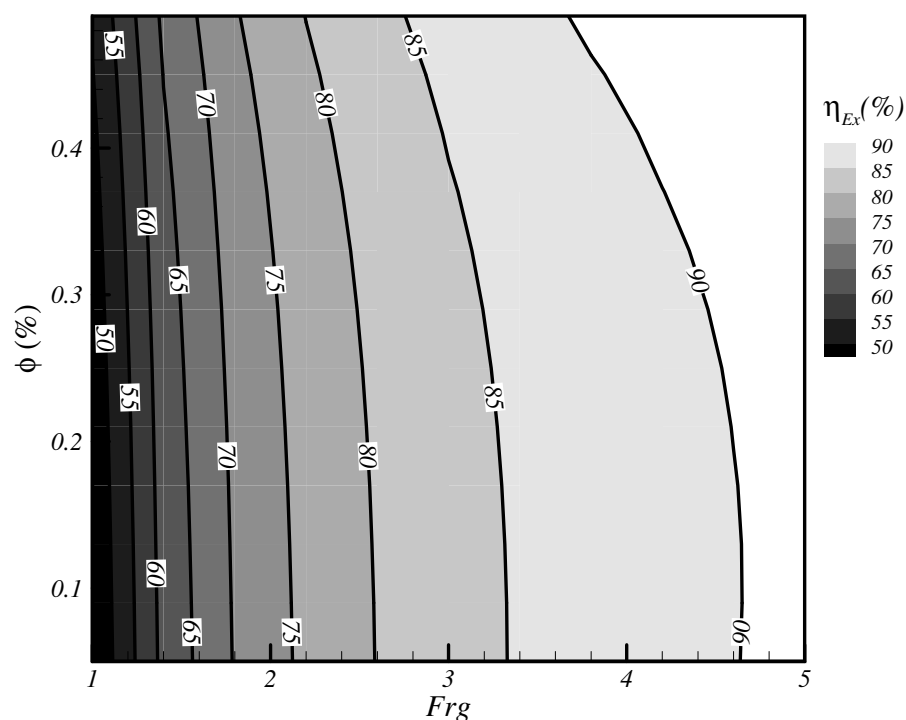


Fig. 5. Exergetic efficiency of the gasifying process as a function of the gasifying relative fuel/air ratio and the moisture content

The effect of  $F_{rg}$  and the bed temperature on exergetic efficiency and cold gas efficiency for RDF gasification are presented (by line & flood contour type) in Figures 7, 8. It is shown that the exergetic efficiency of BFG increases with rising fuel/air ratio as discussed for figures 5 and 6. Higher temperature will increase the exergetic efficiency because of its considerable effect on enthalpy of the product gases (figure7). An increase in bed temperature, as discussed for figure 4, brings about an increase in the concentration of combustible gases and higher heating value which yields an increase in cold gas efficiency (figure8)

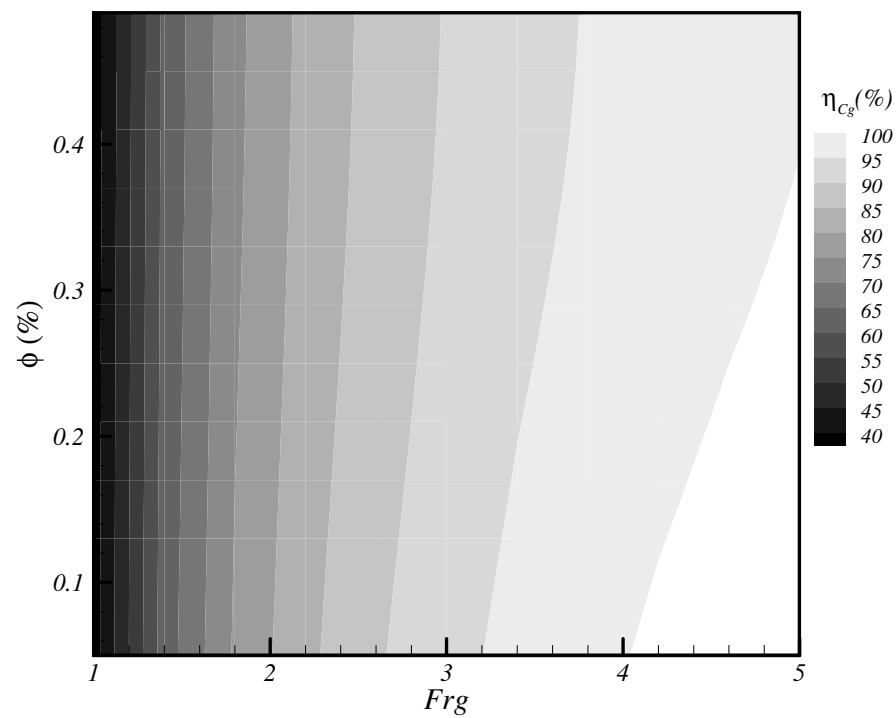


Fig. 6. Cold gas efficiency efficiency of the FBG as a function of the gasifying relative fuel/air ratio and the moisture content

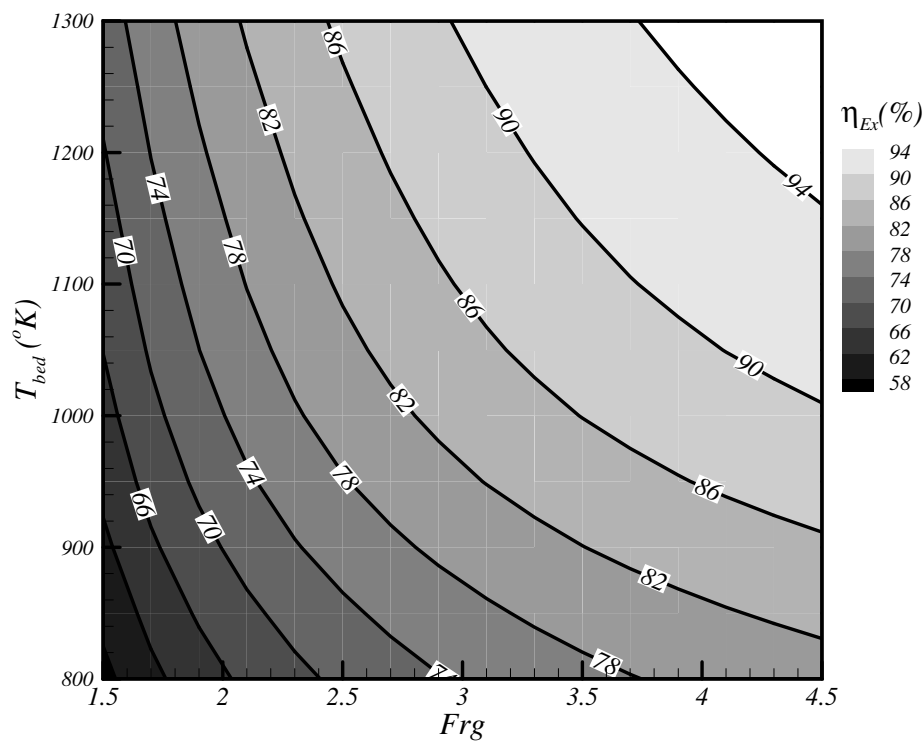


Fig. 7. Exergetic efficiency of the gasifying process as a function of the gasifying relative fuel/air ratio and the gasifying temperature

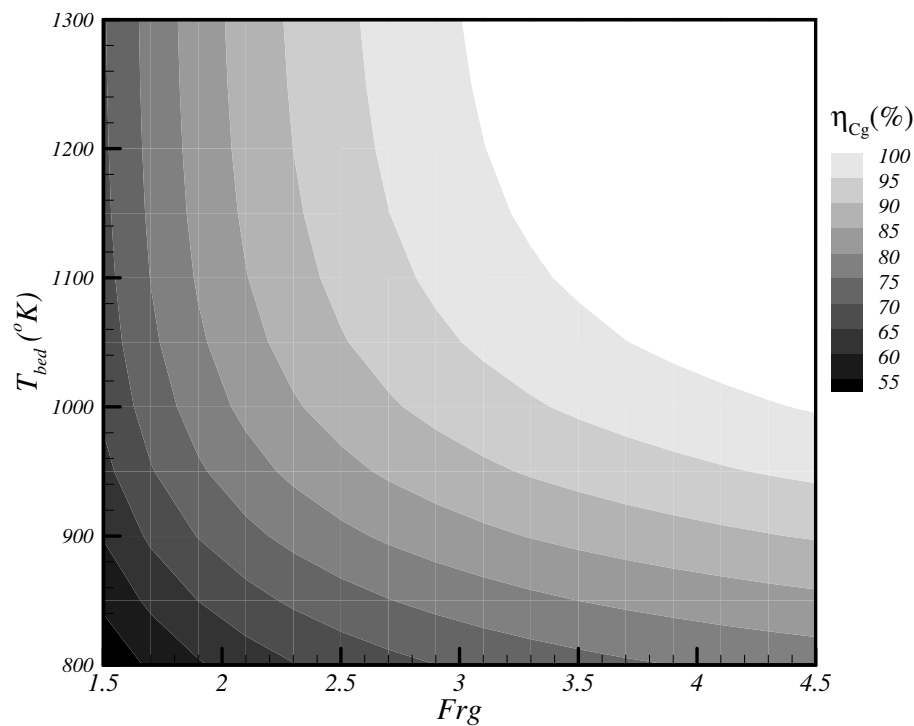


Fig. 8. Cold gas efficiency of the FBG as a function of the gasifying relative fuel/air ratio and the bed temperature

4. Conclusion

An equilibrium model was developed for the biomass waste gasification in the bubbling fluidized bed waste gasification. It was shown that higher moisture would decrease the product gas higher heating value as well as cold gas efficiency while increase the exergetic efficiency. Moreover, It was concluded that higher temperature and higher  $F_{rg}$  would increase both the product gas higher heating value, cold gas efficiency and the exergetic efficiency.

5. Nomenclature

- C mass fraction of carbon
- H mass fraction of hydrogen
- $F_{rg}$  gasification relative fuel/air ratio
- $F_{st}$  stoichiometric biomass waste/air ratio
- M molecular weight (kg/mol)
- $M_{BM}$  biomass waste molecular weight (kg/mol)



N	mass fraction of nitrogen
$m$	molar quantity of air
$w$	molar quantity of biomass waste moisture content
$E_{pg}$	Product gas total Exergy
$E^{PH}$	physical Exergy
$E^{CH}$	chemical Exergy
$\Delta G_T^0$	gibbs free Energy((kJ/mol)
O	mass fraction of oxygen
HHV <sub>db</sub>	higher heating value in dry base
P	pressure
S <sub>0</sub>	standard Entropy(KJ/mol K)
S	mass fraction of sulphur
T	temperature

### Greek symbols

$\phi$	moisture content of the biomass waste fuel
$\eta_{Ex}$	Gasifier exergetic efficiency
$\eta_{cg}$	Cold gas efficiency

## 6. References

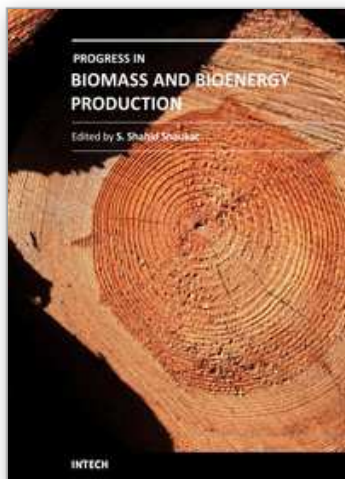
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## **Progress in Biomass and Bioenergy Production**

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Alternative energy sources have become a hot topic in recent years. The supply of fossil fuel, which provides about 95 percent of total energy demand today, will eventually run out in a few decades. By contrast, biomass and biofuel have the potential to become one of the major global primary energy source along with other alternate energy sources in the years to come. A wide variety of biomass conversion options with different performance characteristics exists. The goal of this book is to provide the readers with current state of art about biomass and bioenergy production and some other environmental technologies such as Wastewater treatment, Biosorption and Bio-economics. Organized around providing recent methodology, current state of modelling and techniques of parameter estimation in gasification process are presented at length. As such, this volume can be used by undergraduate and graduate students as a reference book and by the researchers and environmental engineers for reviewing the current state of knowledge on biomass and bioenergy production, biosorption and wastewater treatment.

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